Why We Need to Develop a Multi-Resolution Approach to Global Earth System Modeling.

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http://public.lanl.gov/ringler/ringler.html

How I figured out what to include here?

Essentially, I intersected your "statement of task" with my expertise and ideas.

progress in the nation's climate modeling enterprise over the next 10-20 years

new approaches being planned or discussed

with an emphasis on decade to century timescales and local to global resolution

strengths and challenges of current modeling approaches

discussion of different modeling approaches

relative strengths and challenges of the various approaches

respond to climate change on local to global space scales

appropriate balance between improving resolution and adding complexity

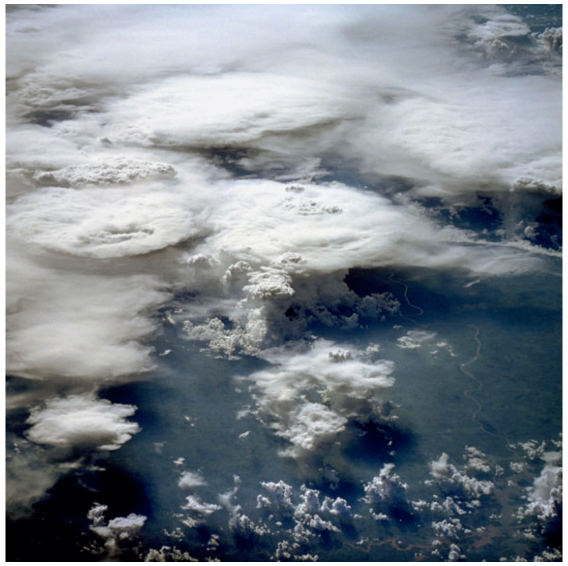
advantages and disadvantages of different approaches to projecting regional climate change

predictions on both regional and global scales

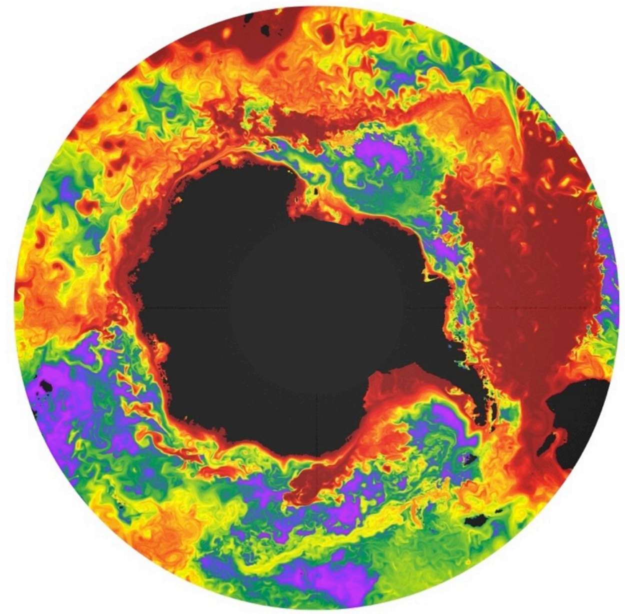
This resulted in a narrowing of scope with respect grand challenges in ocean modeling and a broadening of scope to conceptually include all climate model components.

Underpinning Premise: Presently unresolved scales are likely important to our understanding of global climate change.

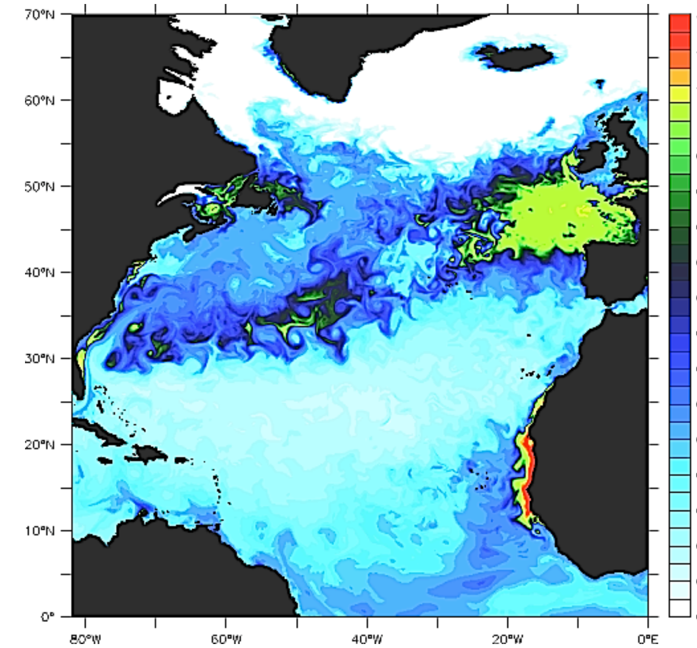
Cloud Processes



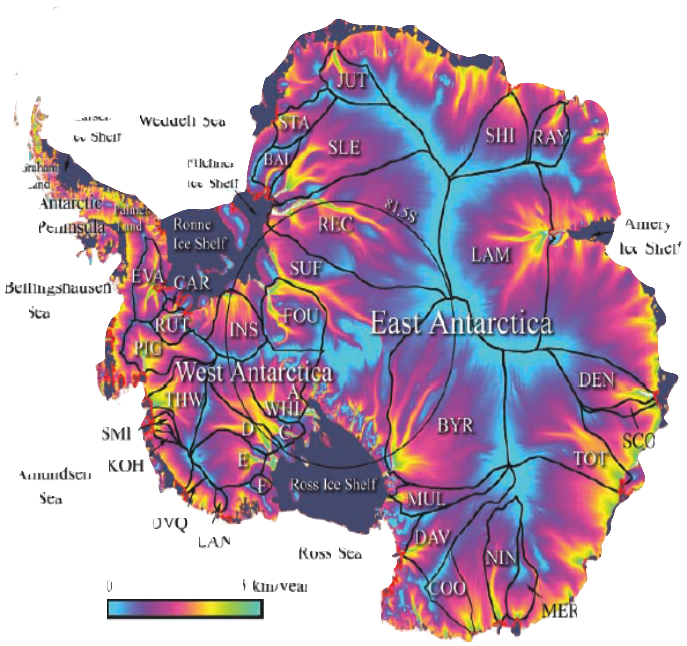
Ocean/Atmosphere Interaction



Ocean Biogeochemistry



Ocean/Ice Shelf Interaction

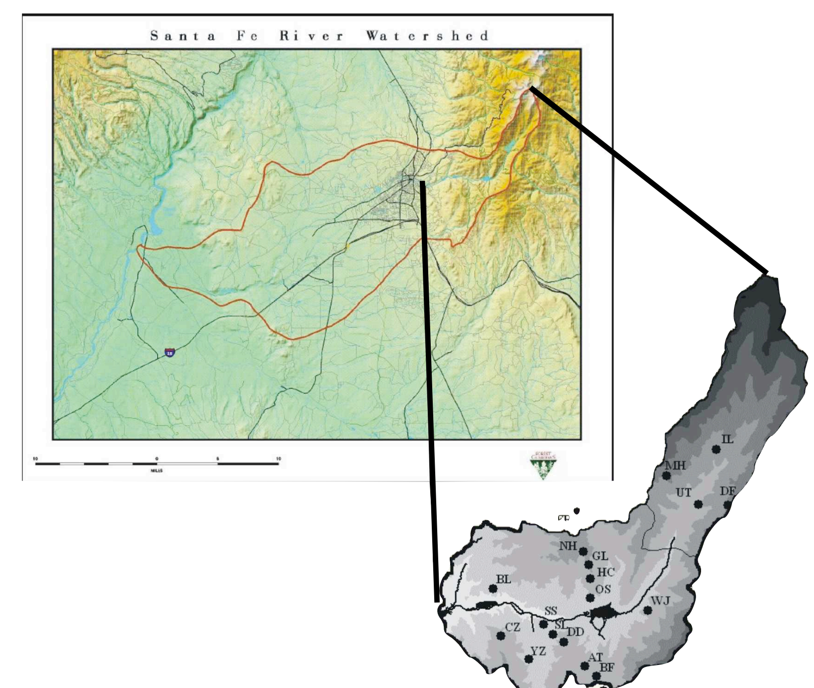


Each of these examples demonstrate scale-sensitive processes that might impact the climate system in a fundamental and important way.

The scale of these processes is O(km).

Studying these processes within the context of a global, quasi-uniform Earth modeling system is nearly impossible.

Hydrology in Complex Terrain



Summary of the Current Approach to Global Climate Modeling

Typical Workflow:

1. Optimize for new computer system
2. Allocate addition computing power
   a. to increased complexity
   b. to increased resolution for each component
3. Conduct new suite of simulations
   a. do science
   b. identify biases and deficiencies
4. Return to 1.

1988
Resolution: ~60 km
Semter and Chervin
Machine: Cray

1992
Resolution: ~45 km
Semter and Chervin
Machine: Cray

1998
resolution: ~30 km
Maltrud et al.
Machine: CM-5

2000
resolution: ~10 km (NA)
Smith et al. (20 years)
Machine: CM-5

2005
resolution: ~10 km (global)
Maltrud et al. (20 years)
Machine: SP3, SP4

2010
resolution: ~10 km
Maltrud et al. (100 years)
Machine: Jaguar

time

Current Approach to Global Climate Modeling: Strengths

1. Experience: For example, the basic structure of our global ocean model was put into place in 1969 by Kirk Bryan.[1]

2. Equitable in terms of temporal/spatial scales: With quasi-uniform meshes we have a clear distinction between what is resolved and what is not resolved.

3. Mitigates deficiencies in physical parameterizations: We know that our parameterizations of unresolved scales are incomplete and sometimes very sensitive to our spatial and temporal resolution.

Parallel Ocean Program
tri-pole, stretched grid

1. Bryan, K. (1969). A numerical method for the study of the circulation of the world ocean. *Journal of Computational Physics*: This contribution used realistic bathymetry and coastlines, z-level coordinates, energy-conserving numerics, structured meshes, non-linear equation of state and a treatment of the external, barotropic mode.

Current Approach to Global Climate Modeling: Weaknesses

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The equitable partitioning of incremental increases in computer resources leads a very solid, but a relatively slowly evolving, approach to global climate simulation.

Goal and Outcomes

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Outcome #1: A broad engagement of climate modelers pressing the boundary of the scales and processes that can be resolved in a global modeling system.

Outcome #2: A relatively rapid scoping of which scale and processes are important for regional and/or global modeling.

Outcome #3: More accurate, global quasi-uniform simulations of the climate will be obtained if we augment this effort with a multi-resolution approach to global climate system modeling.

A Visual Introduction to the Multi-Resolution Approach

The approach is equally valid for atmosphere, ocean, and ice modeling.

Other approaches based on, for example, two-way nesting are also possible and produce the same capability.

The high-resolution region covers 5% of the sphere and, thus, can be computed at 1/20 the cost of its global, quasi-uniform counterpart.

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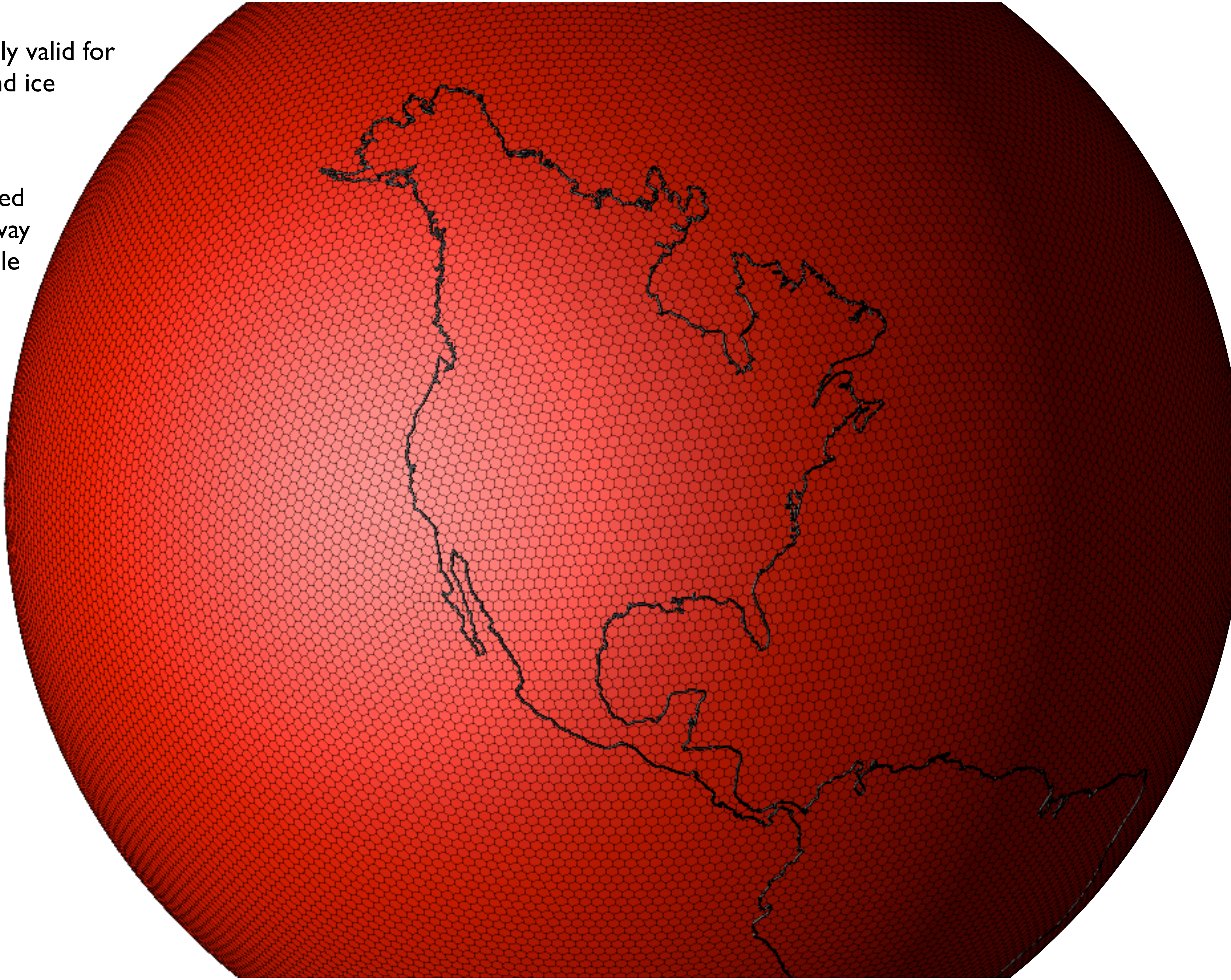

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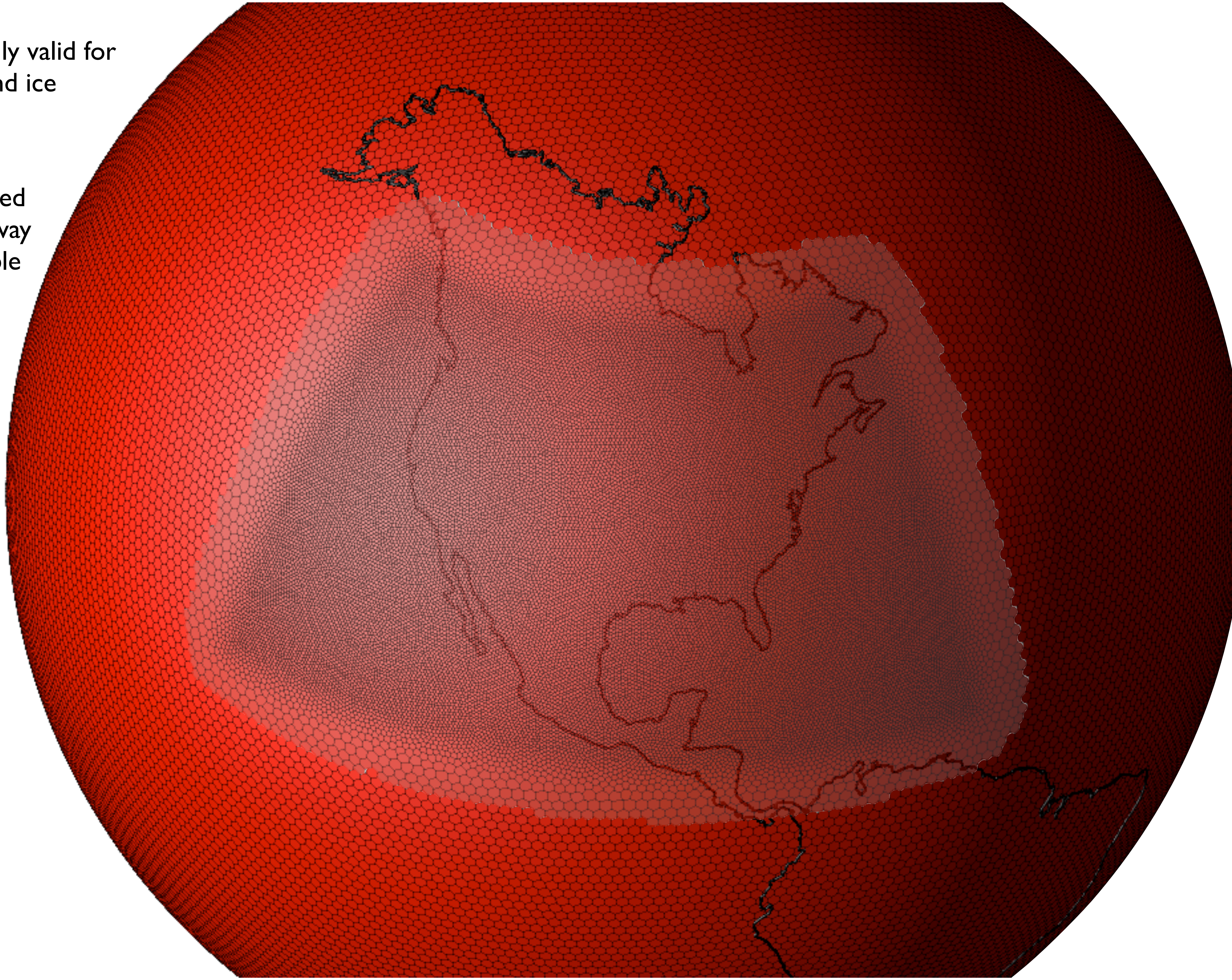
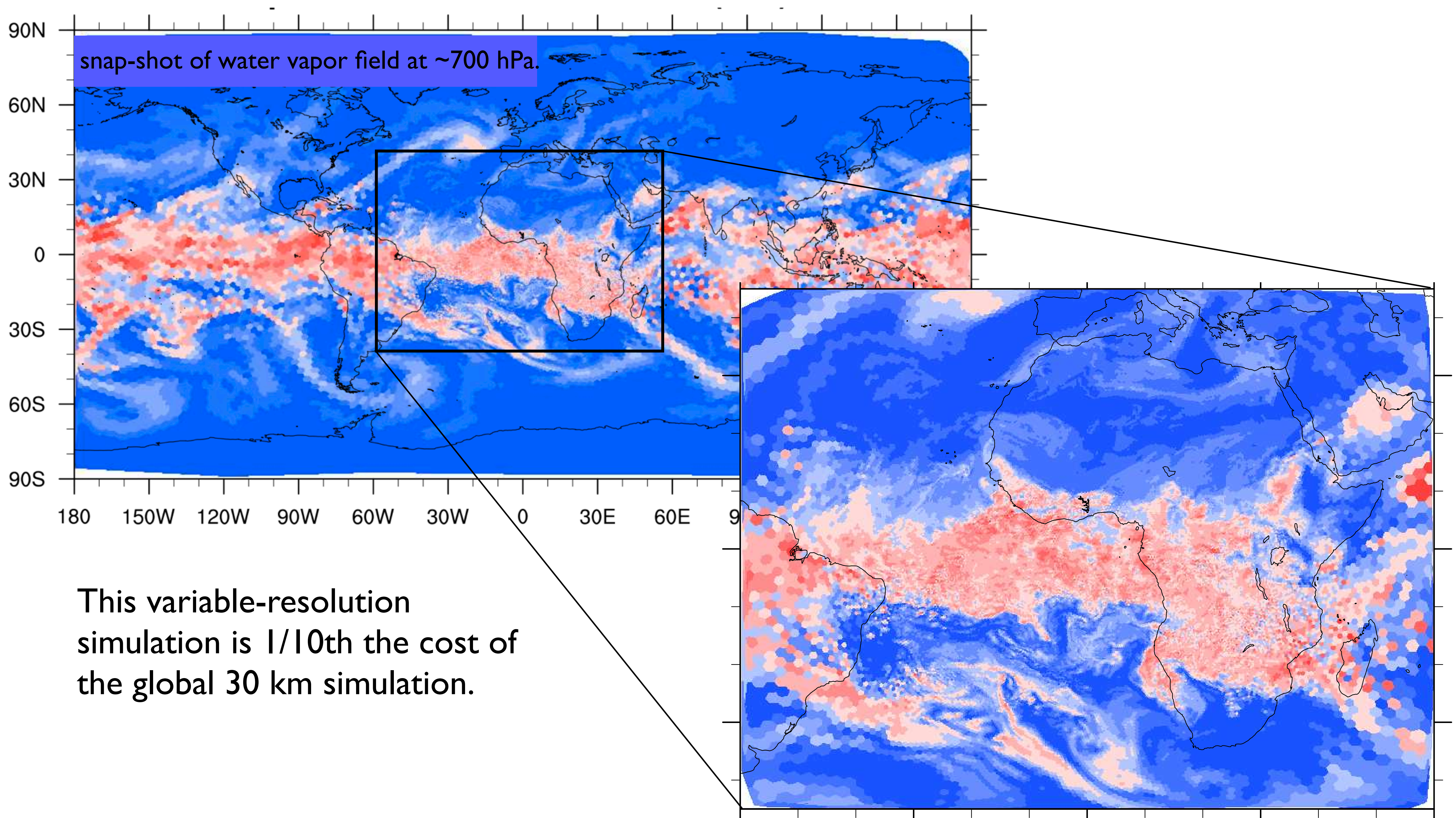


This capability is now present in the NSF/DOE CESM.

Full physics, AMIP-style simulation using the MPAS-A (A multi-resolution atmosphere model). Resolution varies from 30 km the tropical Atlantic / Africa region to 240 km elsewhere.

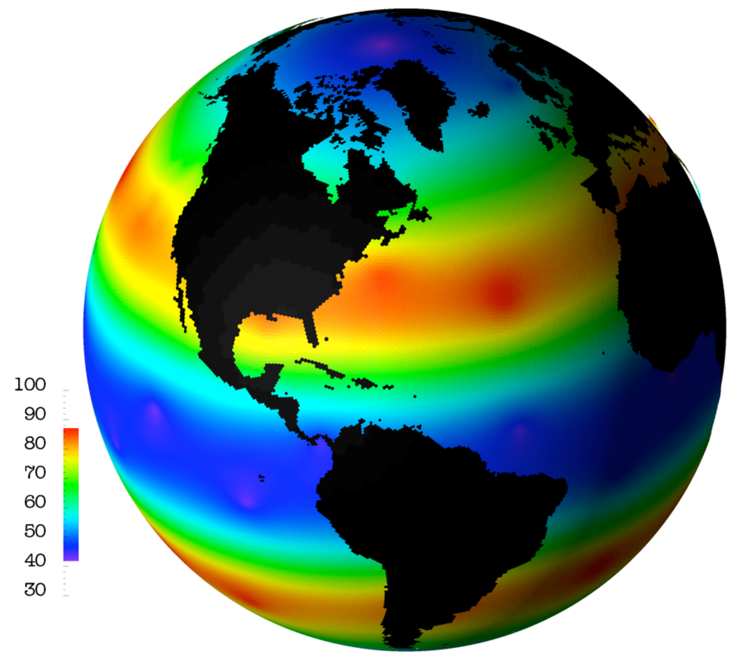


This variable-resolution simulation is 1/10th the cost of the global 30 km simulation.

A stand-alone, multi-resolution, global ocean model

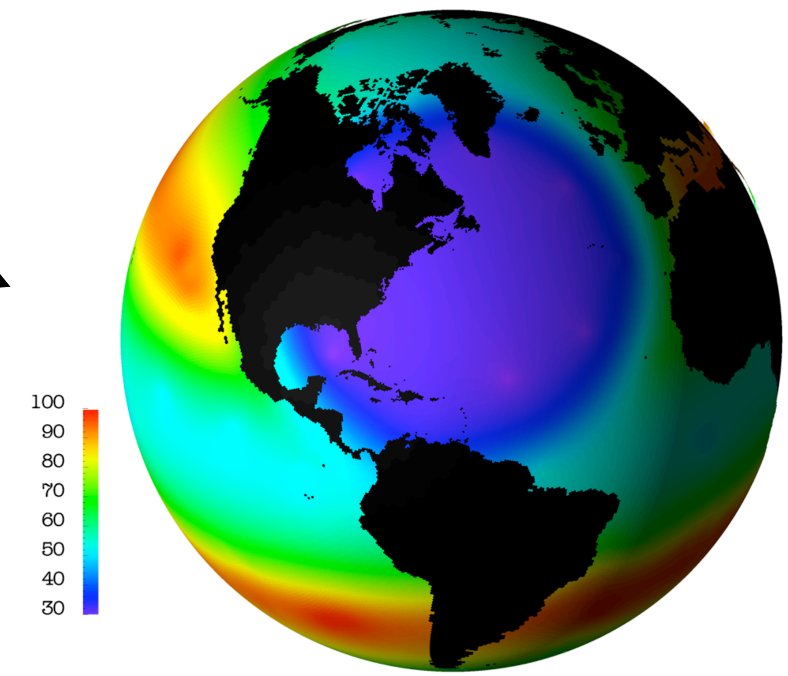
(We are in the process of coupling this model into the CESM.)

R60km: local grid resolution



same number of grid cells

R60kmNA: local grid resolution



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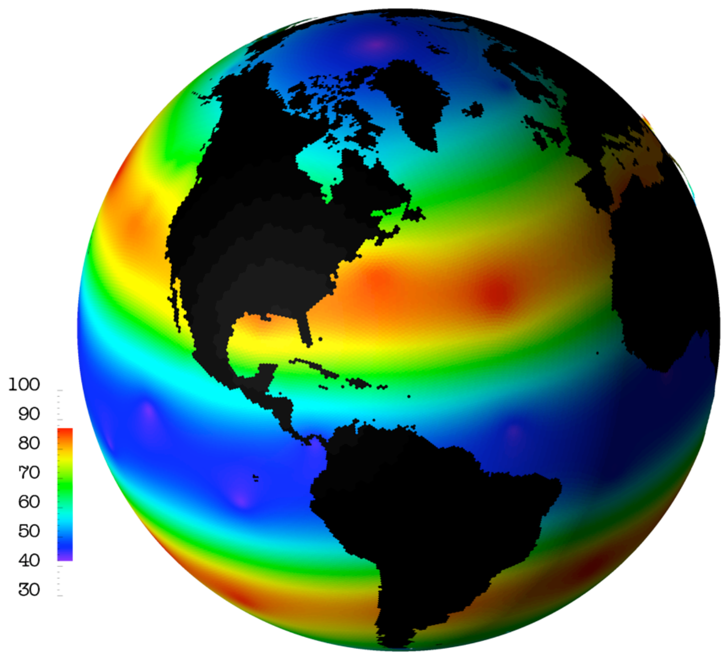

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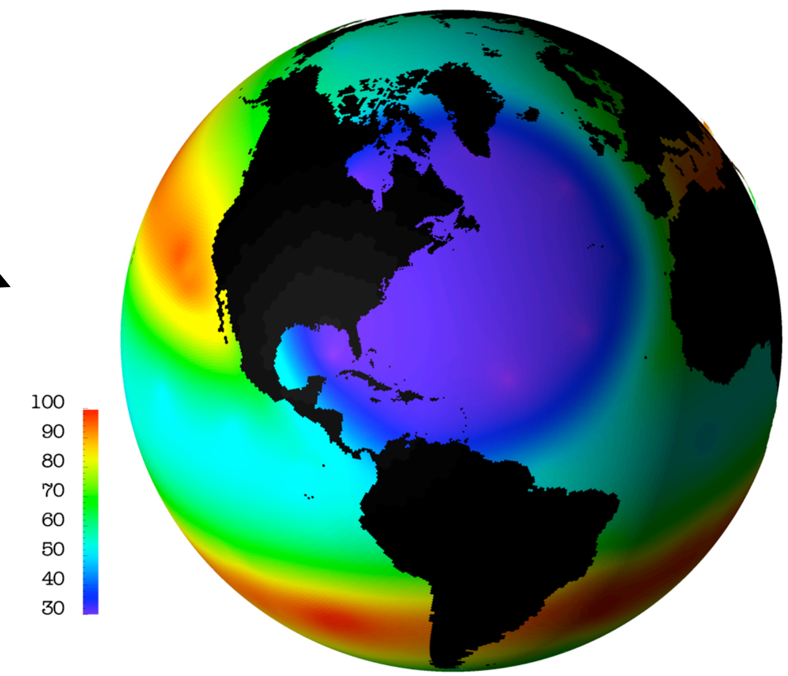
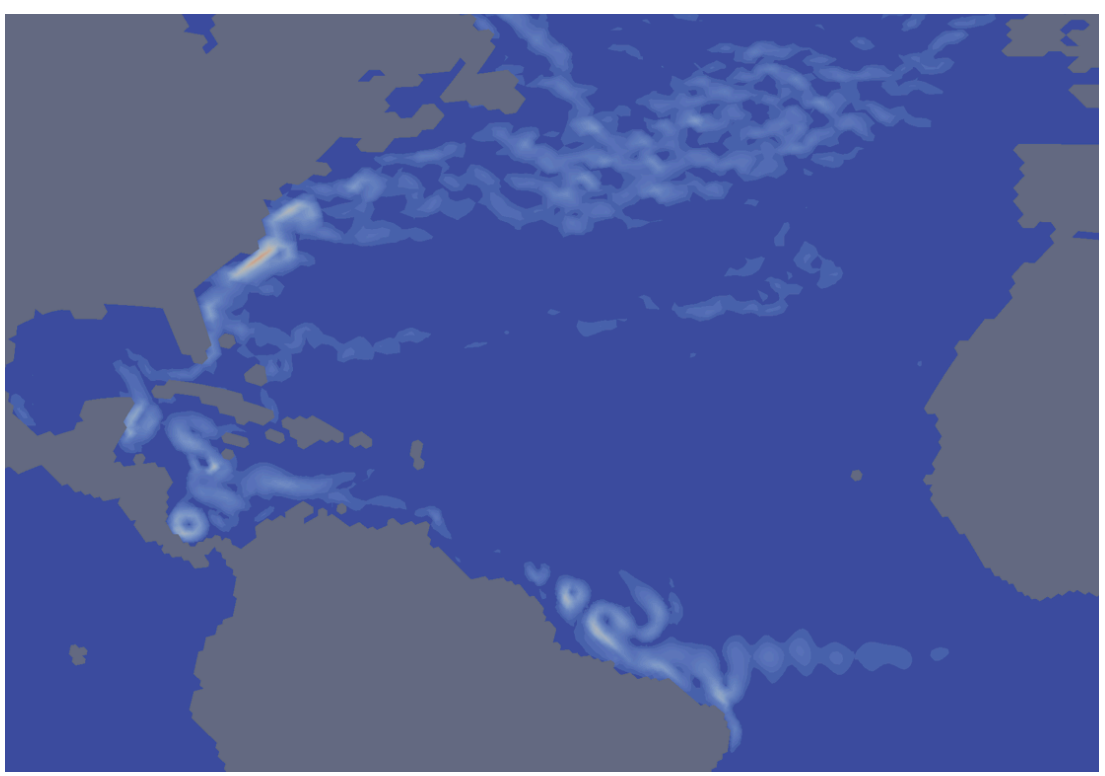
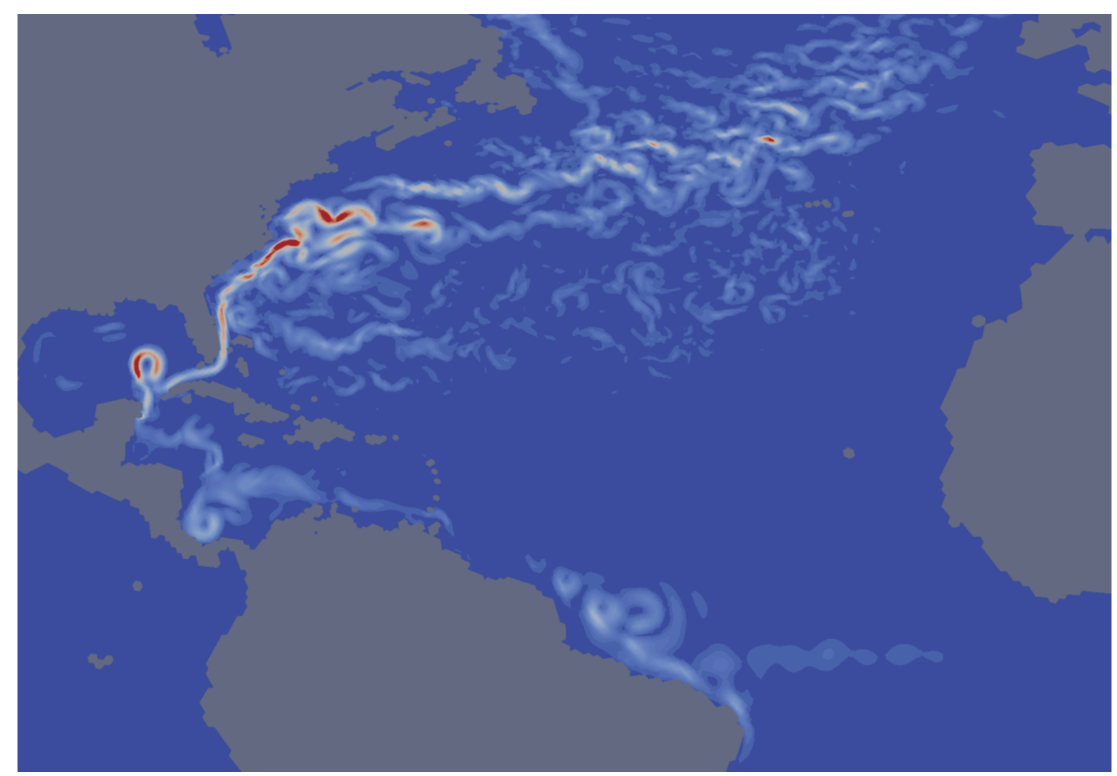




surface kinetic energy

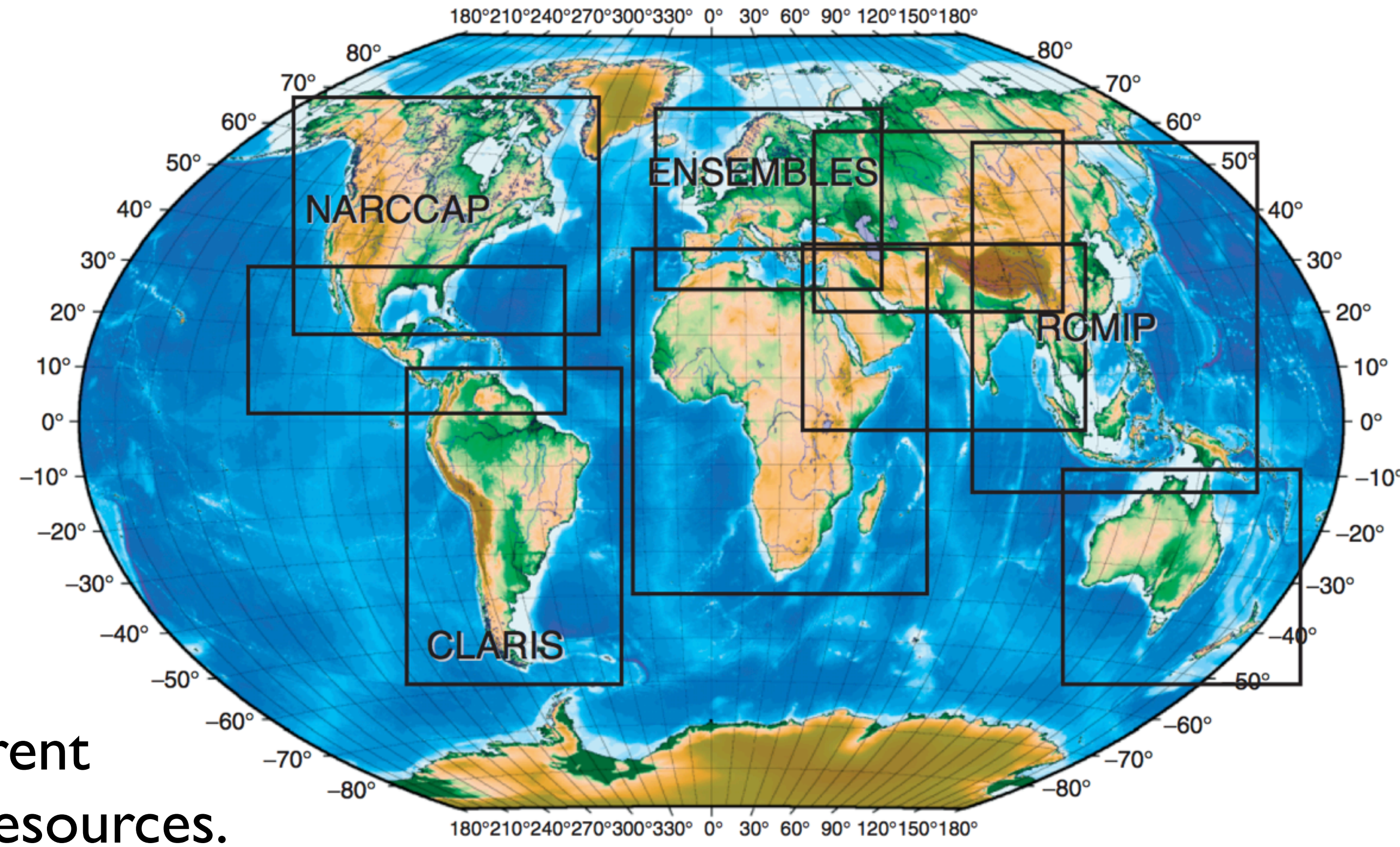


surface kinetic energy

Why develop a multi-resolution capability #1: Study regional climate processes in a global modeling system

(without the need for an INCITE grant!)

Typical Limited Area Domains[1]



The global modeling and regional modeling communities aspire to answer essentially the same question: How does the climate change with increasing levels of of GHGs?

The communities are differentiated primarily by the spatial/temporal scales that are accommodated.

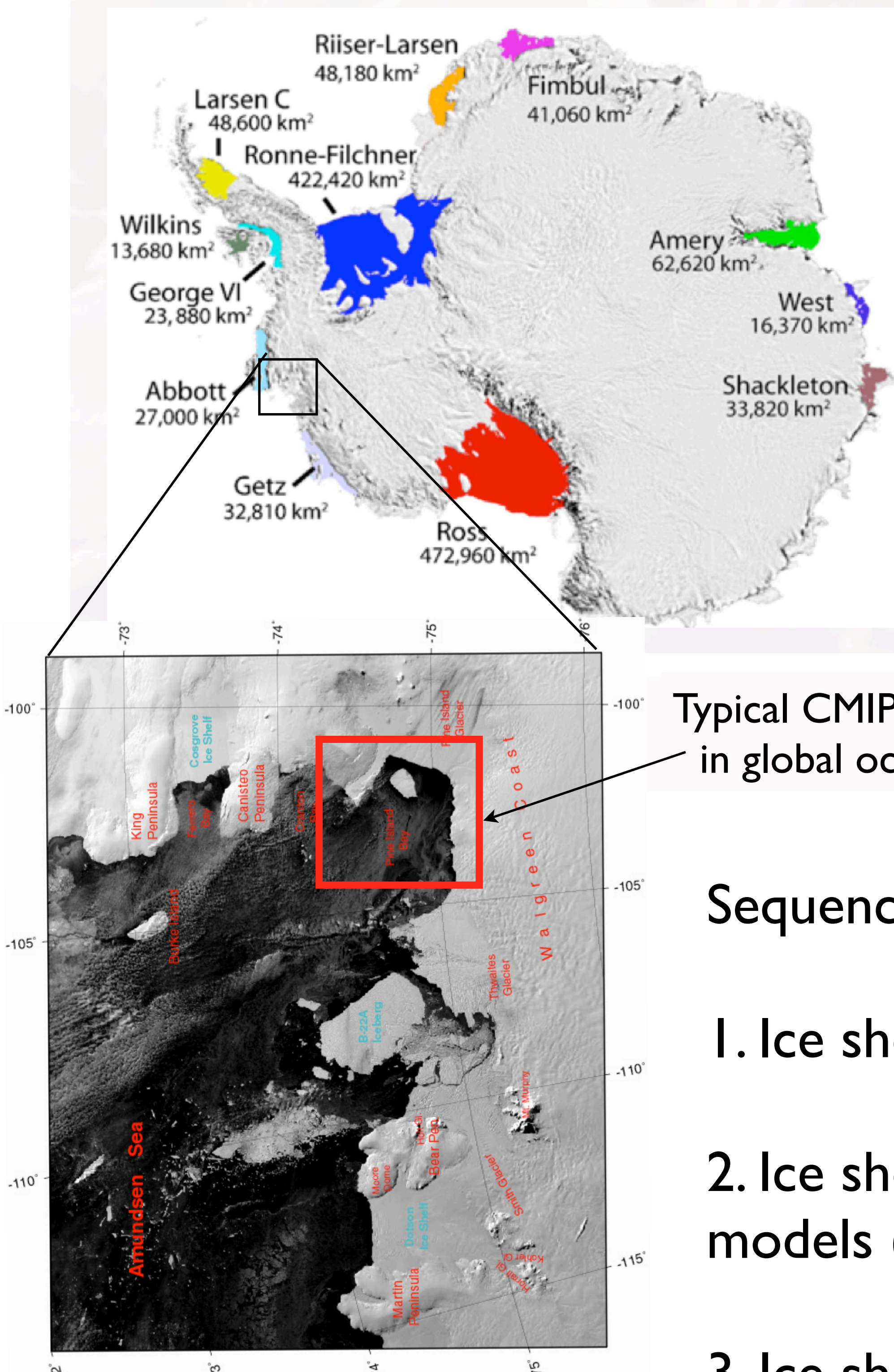
The two communities have simply made different decisions on how to allocate computational resources.

A multi-resolution global modeling approach allows for the exploration of regional-scale climate processes at reasonable expense while maintaining a global modeling framework.

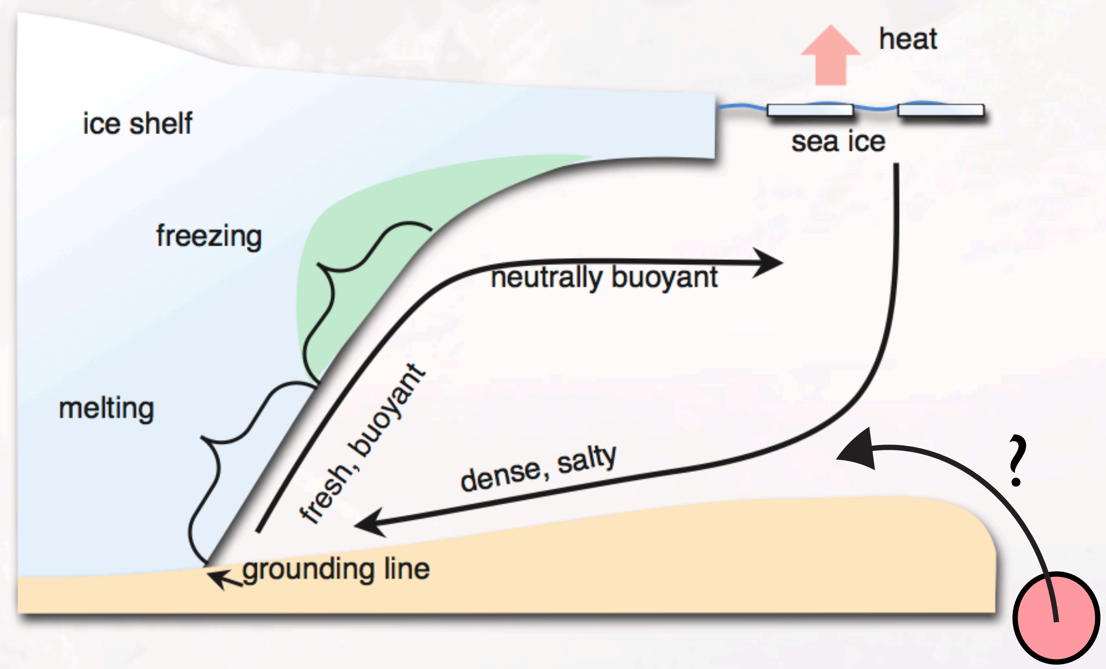
(Note: For the meshes that we are using, the global-variable resolution simulation is only ~10% more expensive than a limited-area simulation using the same high-resolution region. In that, 90% of our degrees of freedom reside in our high-resolution region.)

1. Rummukainen, M. (2010). State-of-the-art with regional climate models. *Wiley Interdisciplinary Reviews: Climate Change*, *1*(1), 82–96.

Why develop a multi-resolution capability #2:
A time-efficient route for the scoping of structural uncertainty.



Typical CMIP-5 resolution in global ocean models



warm, Antarctic circumpolar current water sitting below the shelf.

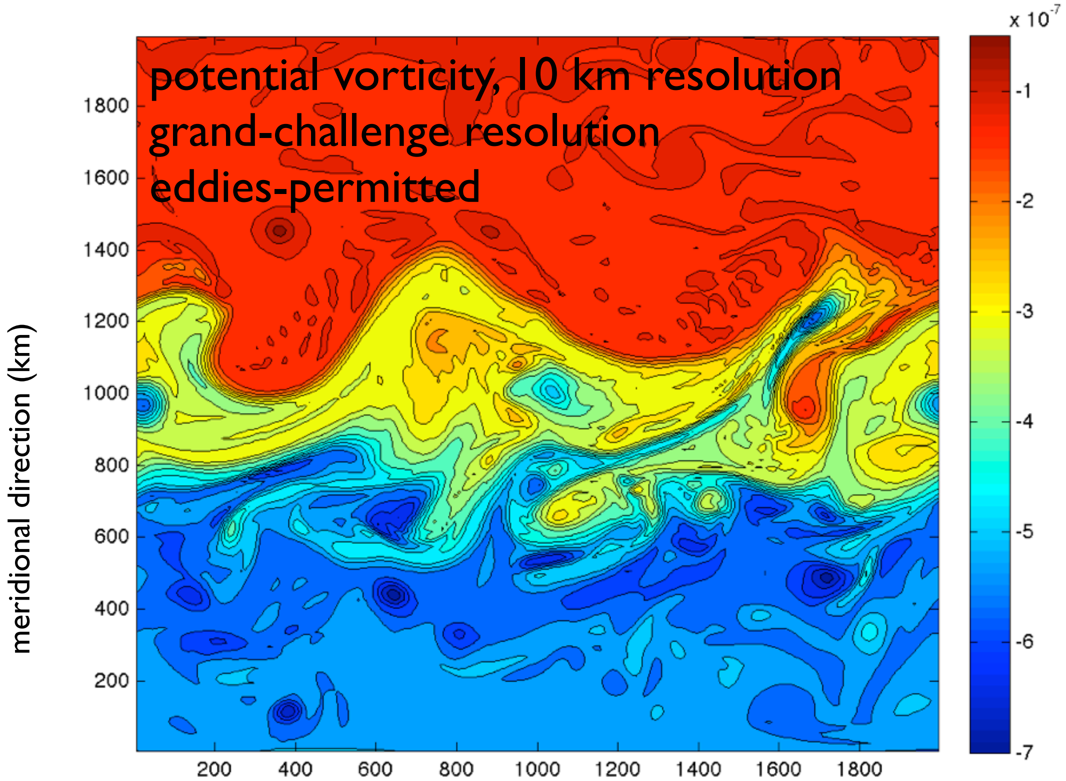
Sequencing for the exploration of ocean / ice-shelf interaction

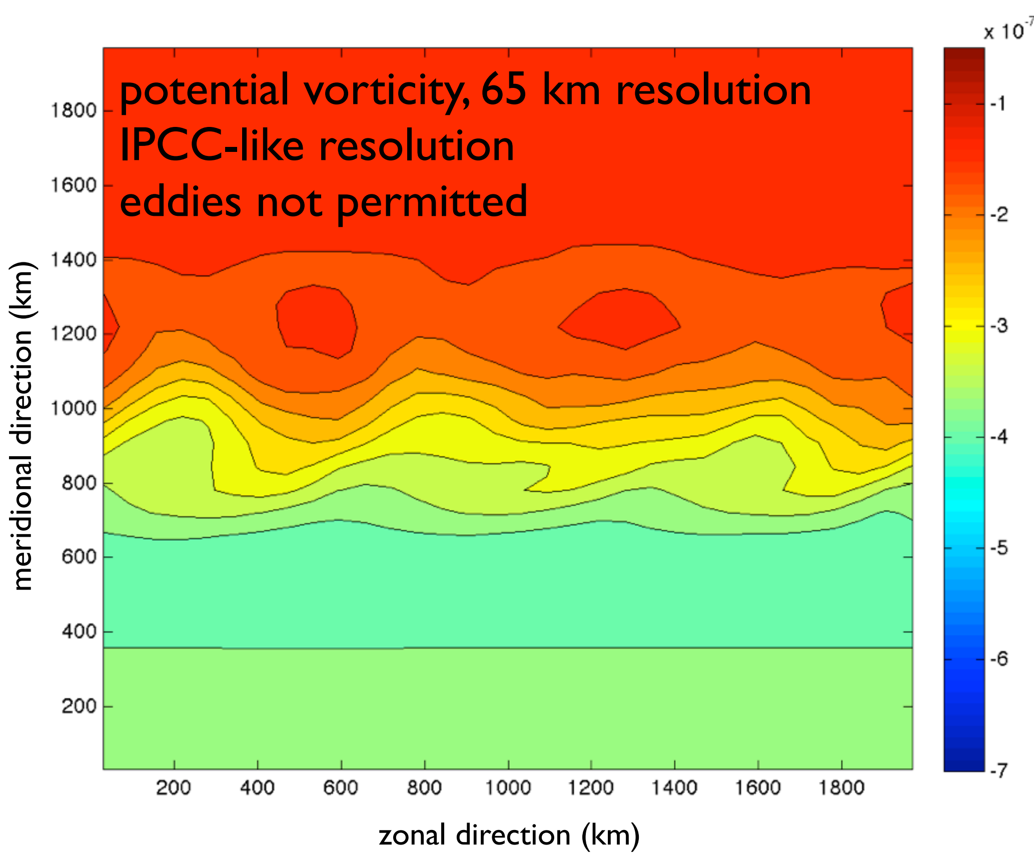
1. Ice shelf models coupled to limited-area ocean models

2. Ice shelf models coupled to global, multi-resolution ocean models (~1 km resolution)

3. Ice shelf models coupled to global, quasi-uniform ocean models

Why develop a multi-resolution capability #3:
A route to more robust physical parameterizations



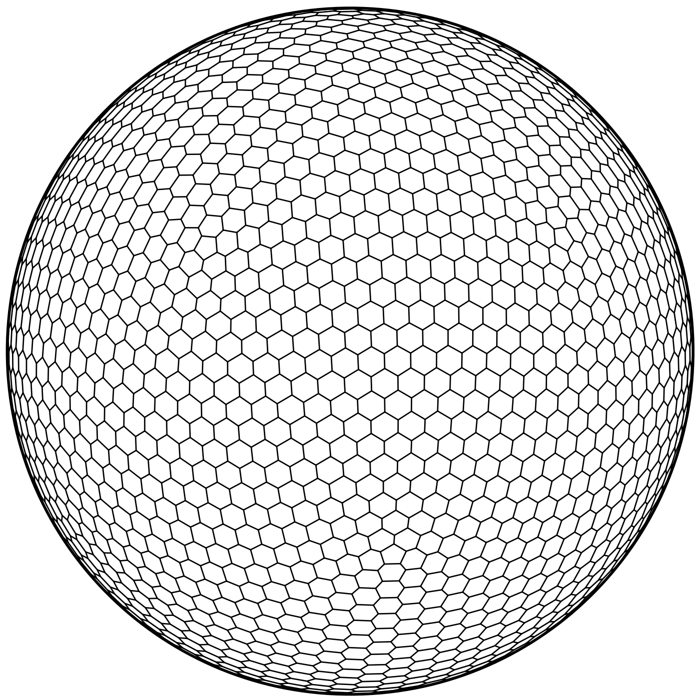


Ocean eddies are a key mechanism in the climate system for the poleward transport of heat. Thus eddies are parameterized in typical climate-change simulations.

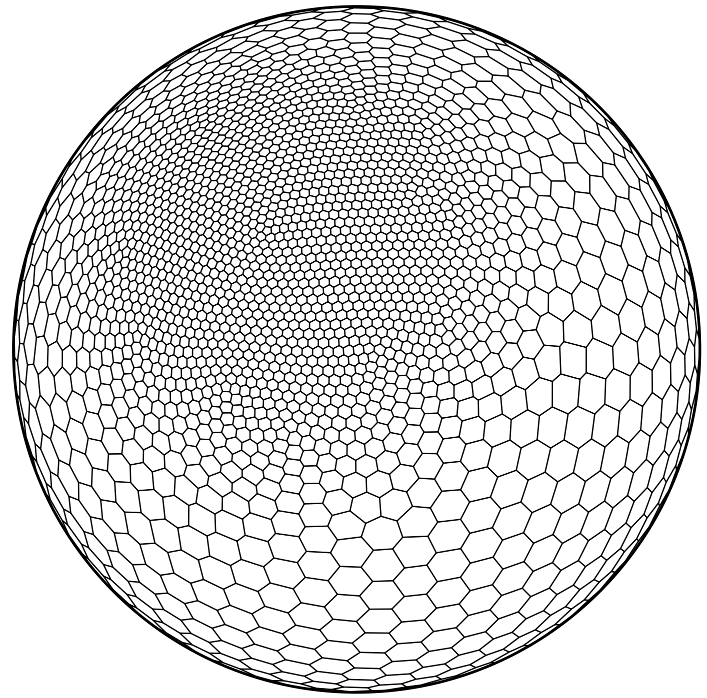
In this case, we use the Gent-McWilliams parameterization where heat transport is a function of kappa (a user-defined parameter).

Unfortunately, kappa is a function of dx. A multi-resolution approach will 1) break scale-dependent parameterizations and 2) allow us to efficiently construct more robust, scale-aware parameterizations since multiply scales are included in a single simulation.

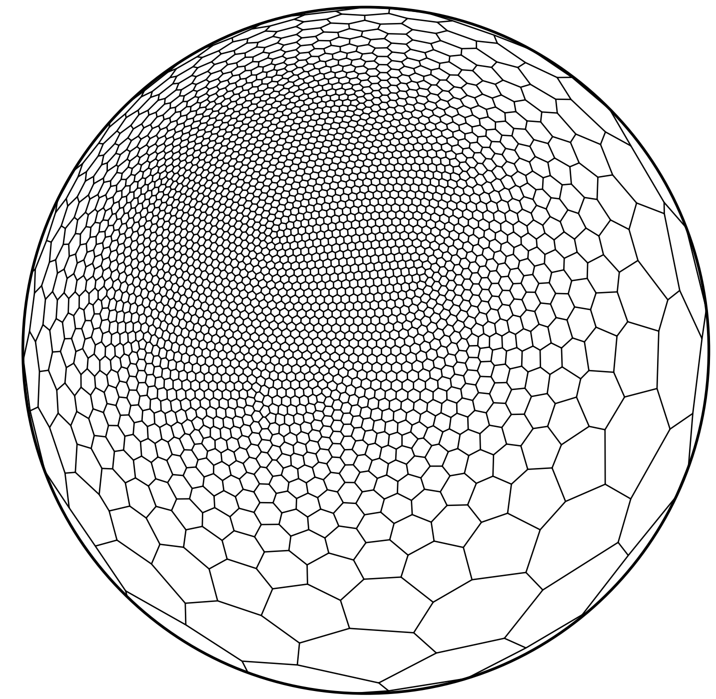
Why develop a multi-resolution capability #4: Serves as a solid global, quasi-uniform model



x1



x4

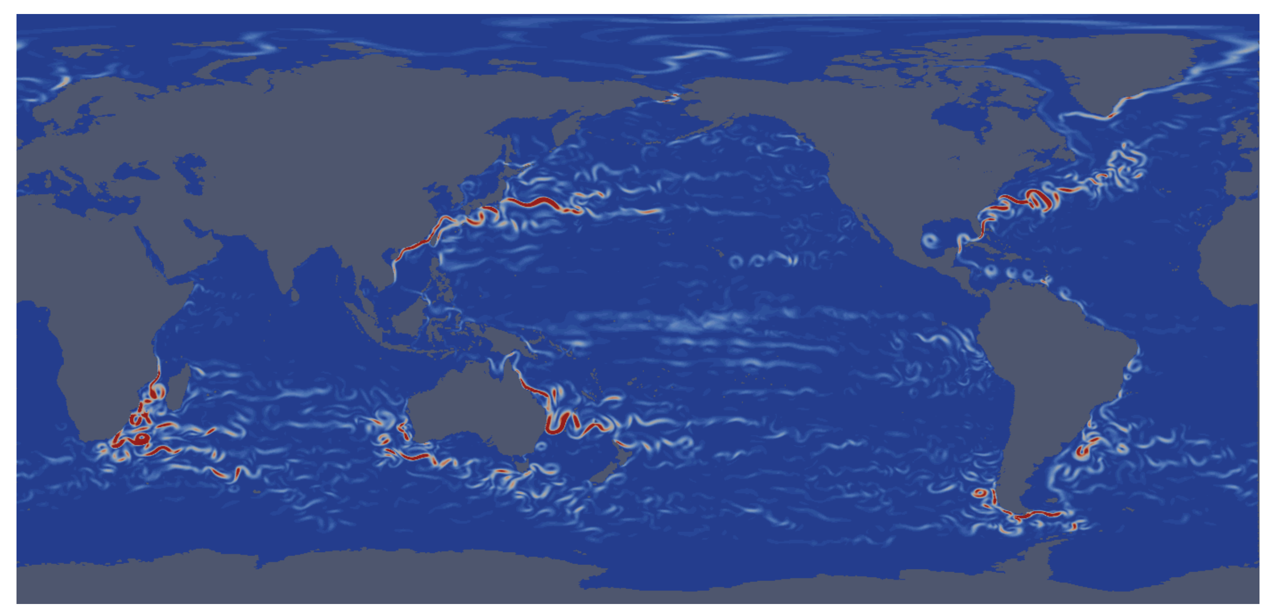


x16

The multi-resolution approach is a generalization of the quasi-uniform approach. As such, we can always recover the traditional, quasi-uniform limit.

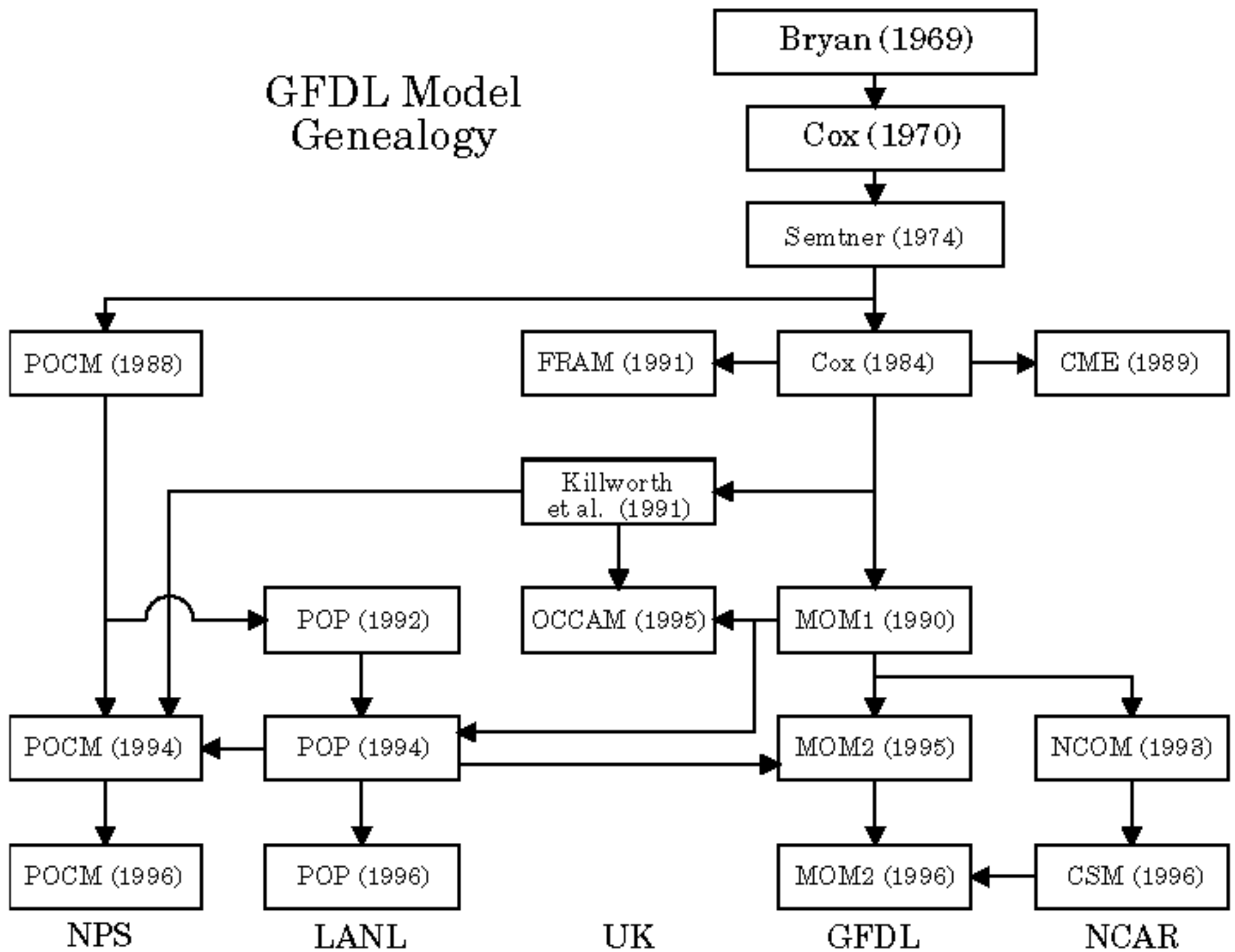
The same idea applied to non-conforming, two-way nested approaches.

First and foremost, a good multi-resolution climate model must be a good quasi-uniform climate model!



surface kinetic energy from a quasi-uniform, 30 km simulation

Why develop a multi-resolution capability #5: Genetic diversity in our multi-model ensemble



The creation of multi-resolution global ocean models will necessarily introduce a significant amount of new "genetic material" into the global climate modeling enterprise.

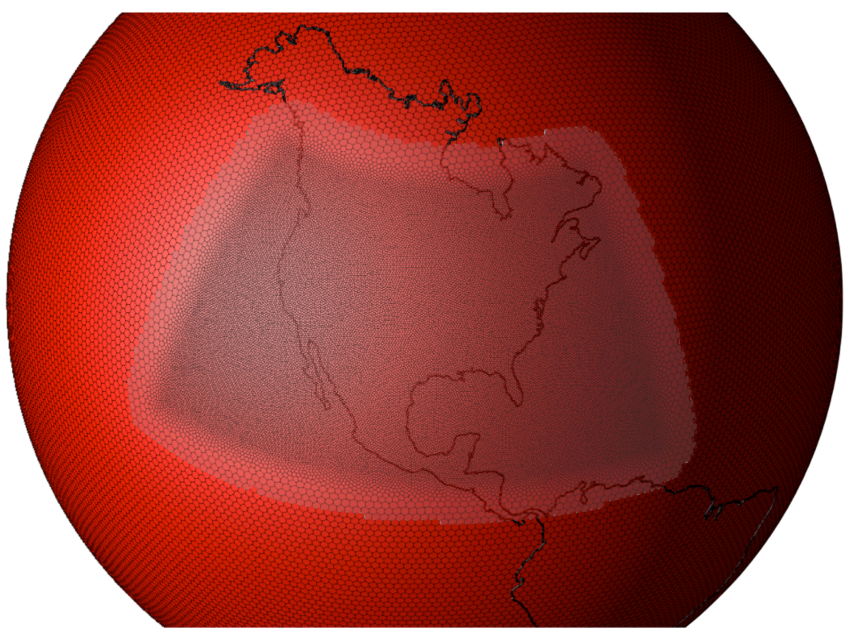
Why develop a multi-resolution capability #6: Mediating the tension between resolution and complexity

An example from the CESM Community Atmosphere Model (CAM):

Complexity: Going from CAM 4 physics to CAM 5 physics cost about 5X.
Resolution: Doubling horizontal resolution typically costs about 8X.
Result of doing both: 40X

Another way to spend that 40X would be to use CAM5 physics at a cost of 5X, increasing the resolution by 6X over US (see figure) and leave resolution unchanged elsewhere.

Which is a better way to spend the 40X?



Since the multi-resolution approach provides flexibility in the allocation of degrees of freedom, it provides flexibility in the allocation of computer resources.

Why develop a multi-resolution capability #7a: A facilitator of inter-disciplinary science: regional climate modeling

The global modeling and regional modeling communities aspire to answer essentially the same question: How does the climate change with increasing levels of of GHGs?

By allowing global models to locally resolve regional-climate spatial/temporal scales, we allow regional and global climate modelers to work within the same modeling framework.

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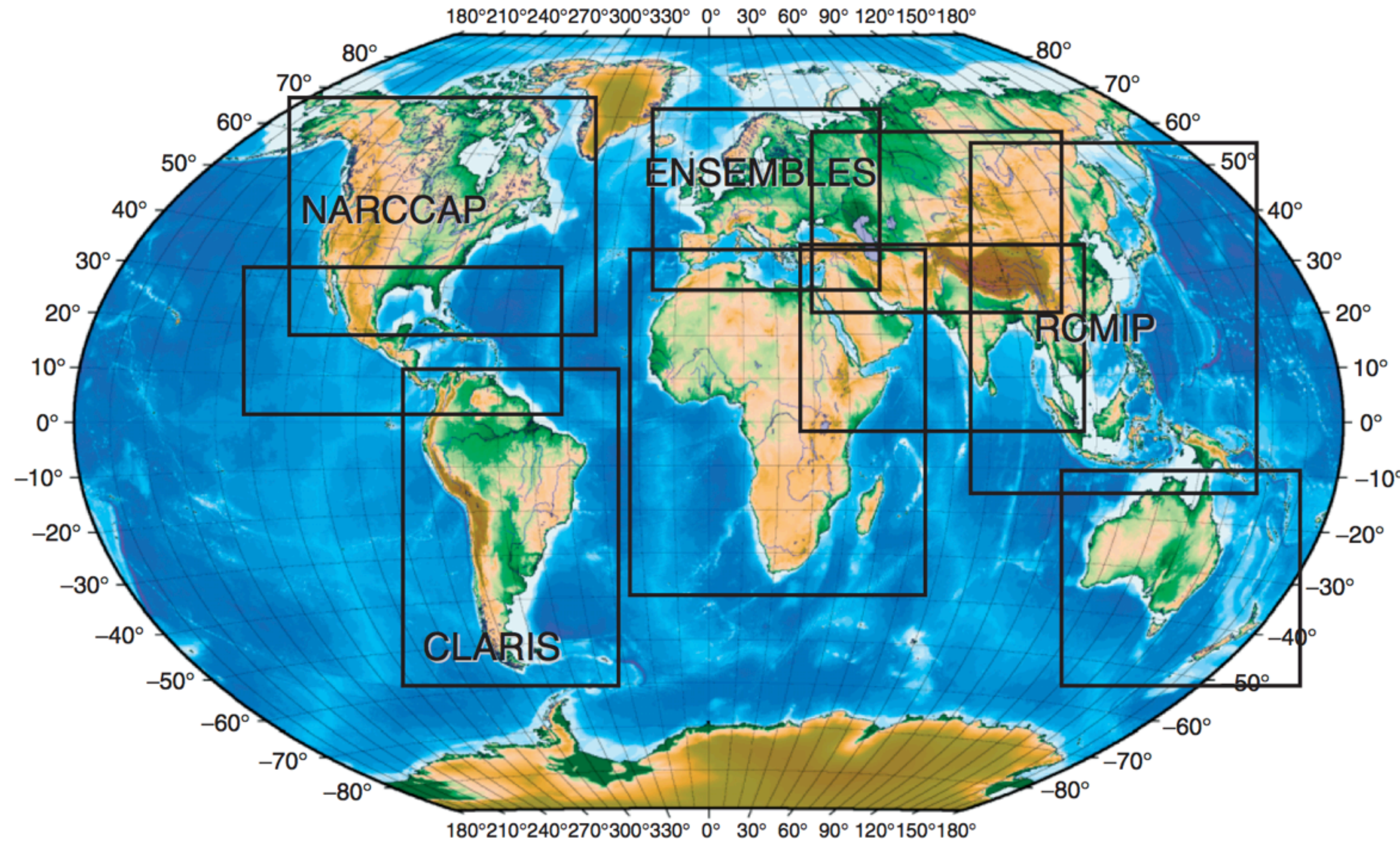


1. Rummukainen, M. (2010). State-of-the-art with regional climate models. *Wiley Interdisciplinary Reviews: Climate Change*, *1*(1), 82–96.

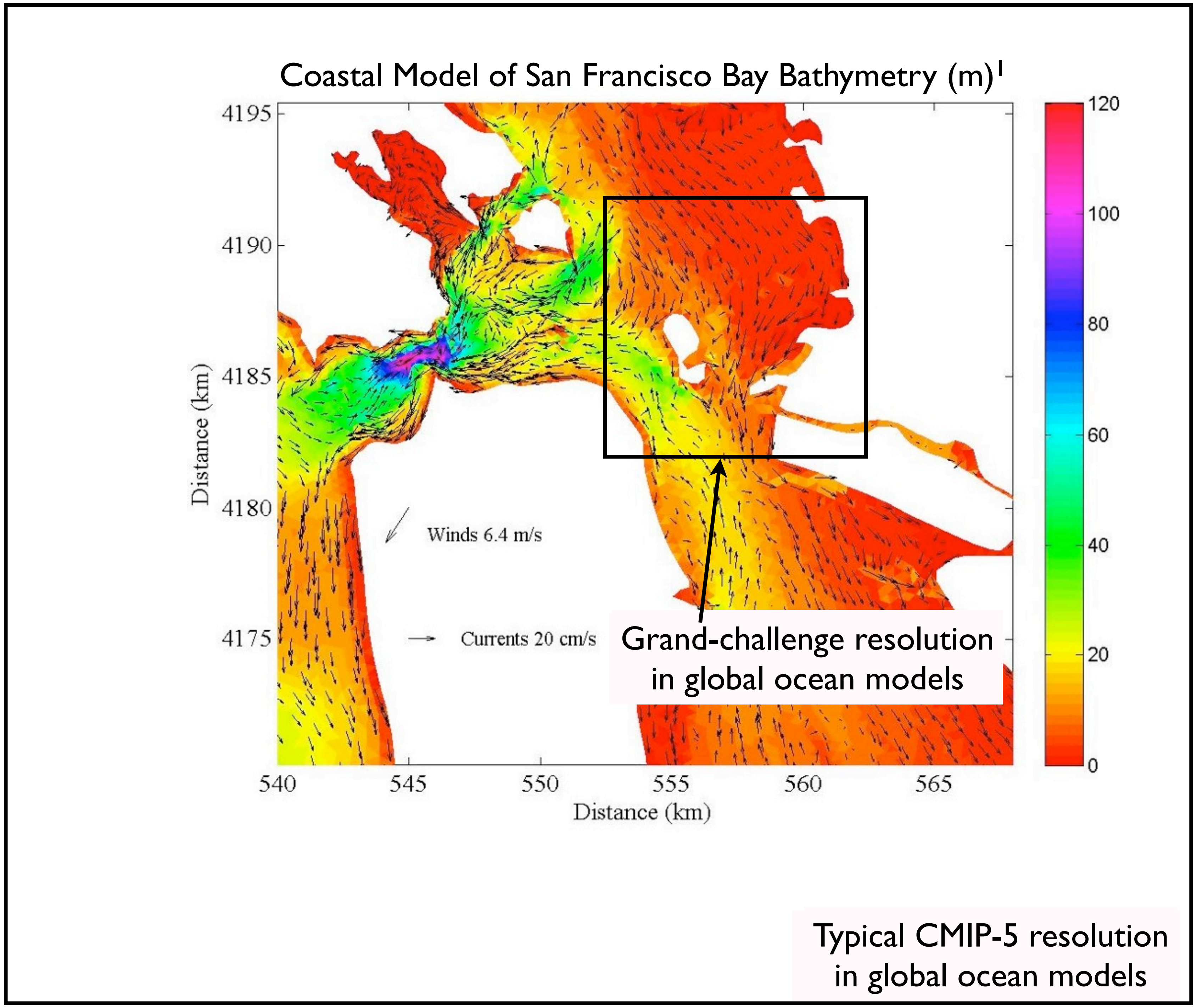
Why develop a multi-resolution capability #7b: A facilitator of inter-disciplinary science: costal ocean modeling

Many societal impacts stemming from anthropogenic climate change will be mediated through coastal processes, e.g. sea-level rise, fisheries, biogeochemical processes, hurricanes ....

Many parameterizations important to coastal modeling (e.g. tides and surface wave dynamics) are migrating into global ocean models.

The multi-resolution approach is common in coastal ocean modeling.

A global ocean model supporting a multi-resolution capability could be used as a foundation to join the global and coastal modeling communities.

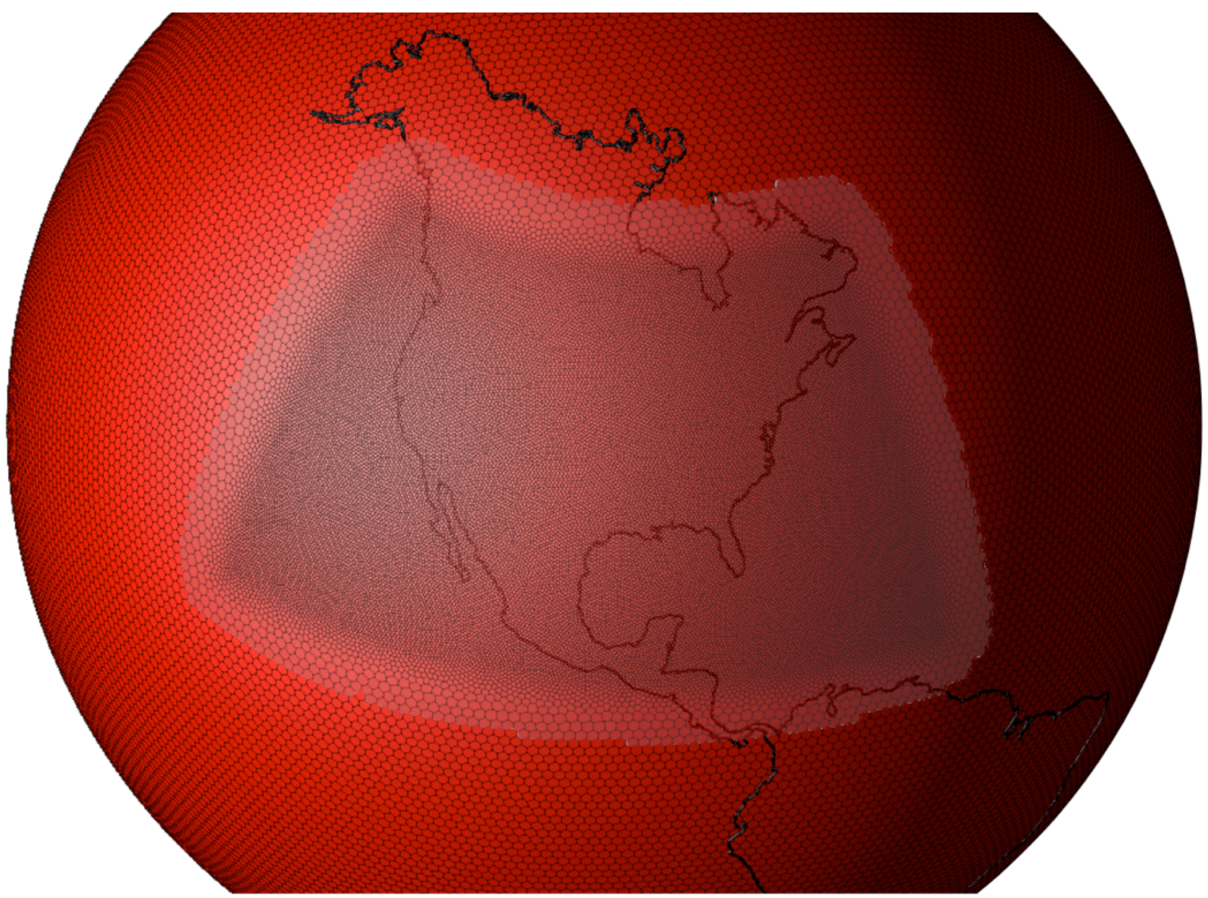


1. Sankaranarayanan, S., and Fringer, O. B. (2010) Dynamics of Low-frequency fluctuations in San Francisco Bay due to upwelling, submitted to the session on Prediction of Multi-Scale/ Multi-Physics Coastal Ocean Flows Using Model Coupling Approaches, 2010 American Geophysical Union fall meeting to held at San Francisco. 13-17, Dec 2010.

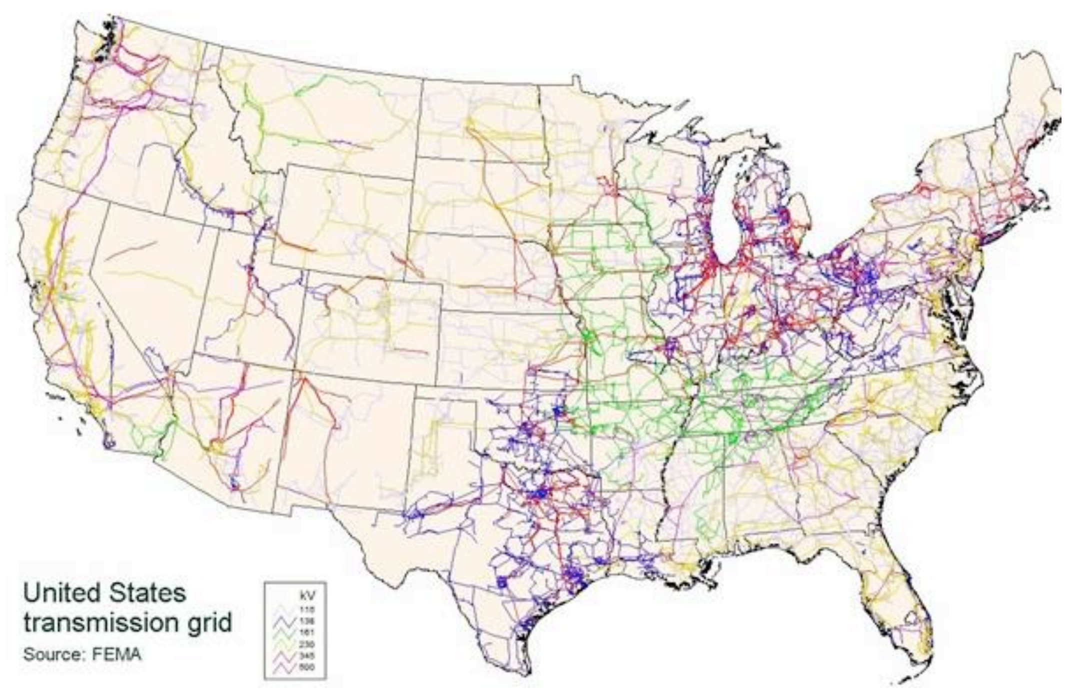
Why develop a multi-resolution capability #7c:
A facilitator of inter-disciplinary science: integrated assessments

We all expect that integrated assessments will continue to develop spatially-distributed models.

Multi-resolution, Earth system models will facilitate the integration of spatially-distributed IA models by permitting resolutions of appropriate scales.



US transmission grid



Challenges and Limitations of the Multi-Resolution Approach

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Some multi-resolution approaches require the use of unstructured data structures.
 (i.e. requires indirect addressing and special attention to algorithm design).

Low-hanging fruit, i.e. likely places to demonstrate value

Places/Situations for "easy wins":

a. systems of relatively small areal extent
   1. Arctic (only 8% of surface area is poleward of 60N)
   2. Antarctic (only 12.5% of surface area is poleward of 45S)

b. systems with strong, regional feedback
   1. coupled ocean/atmosphere simulations in regions of stratocumulus
   2. hurricanes in, say, the tropical Atlantic

c. systems with strong boundary forcing
   1. ocean shelf overflow regions
   2. simulations of snow-pack in topographically-complex regions

d. processes that look at episodic events that benefit from enhanced resolution
   1. heat waves
   2. extreme precipitation events

What is the status of multi-resolution climate models?

1. Atmosphere
    a. MPAS-Atmosphere (NCAR/LANL), hydrostatic, AMIP
    b. MPAS-Atmosphere (NCAR), non-hydrostatic, NWP
    c. CAM-SE (formerly called HOMME), (SNL/NCAR), hydrostatic, aqua-planet
    d. CHOMBO-derived atmosphere, (Michigan/LBNL), under development
    e. ICON, (MPI), non-hydrostatic, initial testing in full physics mode
    f. OLAM (Miami), non-hydrostatic, NWP
    g. Cubed-sphere (GFDL), non-hydrostatic, full-physics, two-way coupling
    h. FIM (NOAA), non-hydrostatic, full-physics

2. Ocean
    1. MPAS-Ocean (LANL), full-physics, eddy-permitting
    2. Finite-Element (AWI, Germany), full-physics, coastal processes
    3. ICON (MPI, Germany), under development
    4. POP/ROMS (NCAR/UCLA), nested, two-way coupling, under development

(Numerous efforts also occurring in land ice modeling.)

(I am sure that this list is not complete.)

Summary

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The creation of a multi-resolution Earth system model will not only lead to a better simulation of the Earth system, but will also promote and accelerate the inter-disciplinary use of these powerful tools.